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Pore Pressure and Fracture Gradient Analysis for Optimising Drilling Performance and Wellbore Stability in the OPU Oilfield, Niger Delta

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ABSTRACT

Inaccurately predicted pore pressures and fracture gradients are the main causes of wellbore instability that cause significant operational and economic challenges in the OPU Oilfield, Niger Delta. Therefore, this study aims to conduct pore pressure and fracture gradient analyses to optimise wellbore stability in the OPU Oilfield. It employed a methodology that incorporated both the well log data (sonic, resistivity and density) and the direct downhole pressure. The approach of Eaton was calibrated and used to forecast the pore pressure, while the fracture gradient was determined using the Leak-Off Test. The findings were effective in determining the specific overpressure regions and in measuring the respective fracture pressures in the field. This definition of the safe drilling window directly relates to the design of mud programs, reducing risks of influx or damage caused by the formation. The research findings conclude that the inclusion of these analyses can greatly improve the stability of the wellbore, non-productive time, and can also give a strong geomechanical model in the development of the OPU Oilfield in later years.

Keywords: Pore Pressure; Fracture Gradient; Formations; Well Log Data, Drilling Performance; Well Stability; Eaton Model; Leak-Off Test; Well Collapse; OPU Oilfield, Niger Delta.

1. Introduction

The Niger Delta basin has continued to be one of the most prolific hydrocarbon provinces in the world, but drilling activities in the province are often hampered by an abnormal pore pressure regime and shallow fracture-pressure windows that pose a threat to wellbore stability (Alao et al., 2025; Osaki L. J 2025). Safe mud-weight design, casing programs and avoidance of drilling hazards like kicks, losses and borehole collapse necessitate the accurate prediction of pore pressure and fracture gradient (Ma et al., 2019). Igbo-Obiakor et al. (2024) discovered that, in the course of the studies conducted in the field of the Niger Delta, the diversity of lithology, compaction disequilibrium, and the conditions of in-situ stresses have a significant impact on the pressure distribution and well integrity. The incorrect estimation of these parameters is prone to cause non-productive time and high cost of operations owing to instability events (Adiele et al., 2025; Lawson-Jack O., 2025). Moreover, wellbore pressure that is maintained at the interval between formation pore pressure and fracturing pressure is essential to ensuring optimal performance at drilling and development of the reservoir (Osaki et al., 2019; Ajayi et al., 2021). Although there are studies of the region, there is still a need to evaluate the pressure regimes at the spatial level, since in the basin, pressure regimes vary. Therefore, the pore pressure and fracture gradient analysis of the OPU Oilfield is essential to enhance the safety of drilling and the optimal stability of the wellbore.

1.1. Study Objectives

The aim of this study is to execute a pore pressure and fracture gradient analysis for optimised wellbore stability in the OPU Oilfield, Niger Delta. The objectives are to:

1) Estimate the formation of pore pressure in the OPU Oilfield using well log data and pore pressure prediction models;

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2) Determine the fracture gradient of the formations within the OPU Oilfield using leak-off test data;

3) Predict the distribution of the formed fracture gradient in OPU Oilfield;

4) Evaluate the wellbore stability conditions of the OPU Oilfield formations through geomechanical analysis of in-situ stresses and rock mechanical properties; and

5) Recommend optimised drilling strategies that minimise drilling risks while improving operational efficiency in the OPU Oilfield.

2. Literature Review

Pore pressure and fracture gradient examination are essential factors of geomechanical research undertaken to provide stability to wellbores during the drilling process. There are also scenarios of abnormal pressure regimes in the sedimentary basins like the Niger Delta, which is caused by rapid sedimentation, disequilibrium compaction, and tectonic stress conditions (Alabere and Akangbe, 2021). Igbo-Obiakor et al. (2024) noted that precise forecasting of pore pressure and fracture gradients can be used to establish the safe range of drilling, hence reducing the risks of kicks, blowouts, lost circulation, and borehole collapse.

Well log data, leak-off tests, and geomechanical modelling have been used in empirical studies in the Niger Delta to estimate the regimes of pressure and drilling operation optimisation. From their study, Adiele et al. (2025) found overpressure areas and fracture gradient limits that govern safe weights of mud to be used in drilling. The geomechanical study of Niger Delta fields carried out by Wilfred et al. (2021) revealed that fluctuations in pore pressure and minimum horizontal stress have a strong impact on drilling risks and wellbore stability.

Rock mechanics and the effective stress theory are the theoretical foundations upon which the pressure of the pores and fracture gradient are predicted. The concept of effective stress by Terzaghi defines that formation stability is a factor of overburden stress, pore pressure, and horizontal stress equilibrium (Andrew, 2024). In fractured zones, stress-induced breakouts are common, with the highest horizontal stress (Kianoush and Jamshidi, 2026). Eaton-based equation and fracture gradient correlations based on data of the leak-off tests are widely used analytical equations used to estimate the subsurface pressure regimes and safe margins of drilling (Mbamalu and Nwosi, 2024). These theoretical frameworks are used to conduct geomechanical assessment and as the basis of wellbore stability analysis of complex petroleum basins like the OPU Oilfield in the Niger Delta.

3. Geology of the Study Area

The OPU Oilfield is an onshore field in the Niger Delta in Rivers State, where the prolific cumulative amount of hydrocarbons and intricate regimes of subsurface pressure are high (Opara and Lawson-Jack, 2018). Geographically, the OPU field is located in the Niger Delta petroleum province, which is predominantly comprised of the Benin, Agbada and Akata Formations that regulate the reservoir distribution, the overburden stress, and the pore pressure formation. Quick sedimentation and compacting shale in the Agbada Formation frequently build up unnatural pore pressure that can largely affect drilling safety and stability of the wellbore (Iheanyichukwu and Jack, 2018), as presented in Figure 1. Accurate forecasting of the pore pressure and fracture gradient is therefore a necessity that is necessary in designing the optimum mud weight and avoiding the drilling hazards like lost circulation and kicks (Adiele et al., 2025). This study is hence applicable to the OPU Oilfield due to the fact that it is a typical system of the recently formed Niger Delta reservoir with variable lithology, pressure compartments, and active drilling activities, which makes it ideal for assessing geomechanical parameters that are needed to optimise wellbore stability.

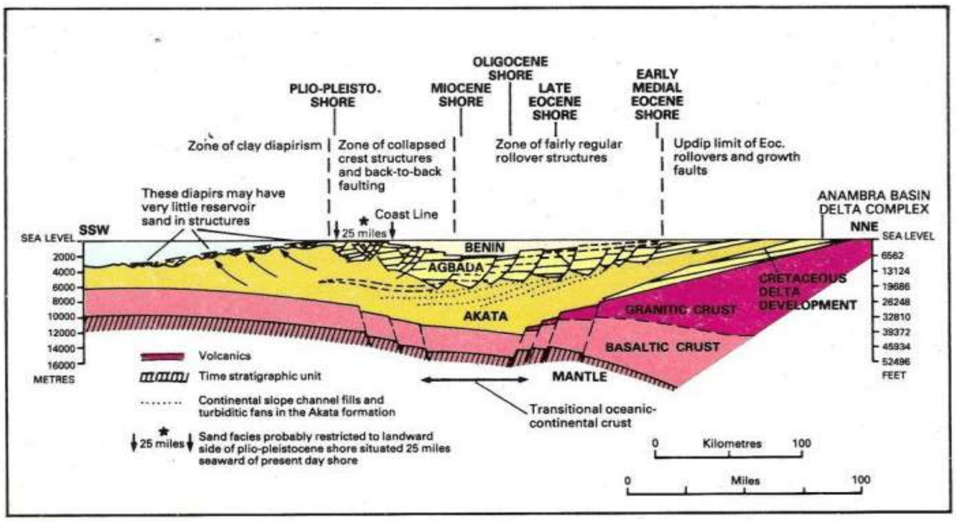
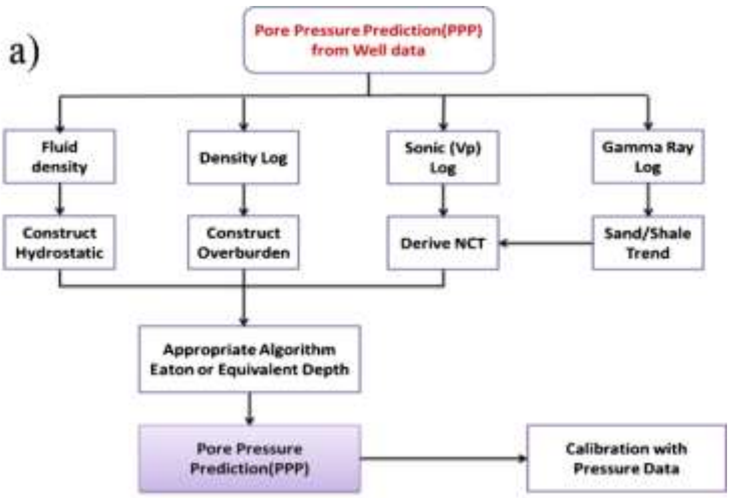


Figure 1. The Location Map of OPU Oilfield, Niger Delta, Showing Benin, Akata, and Agbada Formations with Their Respective Shores (Iheanyichukwu and Jack, 2018).

4. Methodology

4.1. Estimation of the Formation of Pore Pressure in the OPU Oilfield

Well log data, such as density and gamma-ray logs, were used to estimate formation pore pressure in the OPU Oilfield, which is in the Niger Delta. The first shale intervals were determined based on gamma-ray logs, followed by a Normal Compaction Trend (NCT) being determined based on sonic travel time data. Then, the Eaton pore pressure prediction model was used to estimate pore pressure using deviations on NCT and overburden stress values, as described by Wahidaulhusna and Sukmawati (2025). Comparison tables of the parameters obtained using the logs and the pressures were created to facilitate analysis and the definition of the abnormal regions of pressure, as presented in Figure 2.



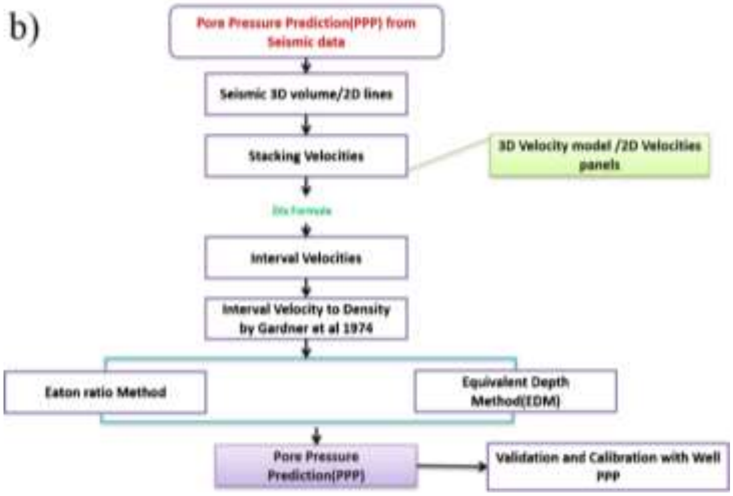


Figure 2. Comparison Tables of the Parameters Obtained Using the Logs and Obtained Pressures to Enhance Analysis and The Definition of the Abnormal Regions of Pressure in OPU Oilfield (Wahidaulhusna and Sukmawati, 2025).

4.2. Determination of the Fracture Gradient of the Formations within the OPU Oilfield

Leak-Off Test (LOT) results that were collected upon the installation of casing were used to determine the fracture gradient of the formations in the OPU Oilfield located in the Niger Delta. Al Ramadan (2024) noted that the test involved drilling fluid into the formation until the pressure at which the formation would start fracturing was monitored. The relationships between formation depth and hydrostatic pressure were used to convert the leak-off pressure to fracture gradient. A depth-pressure graph was prepared to represent the profile of fracture gradient along the interval drilled, as presented in Figure 3.

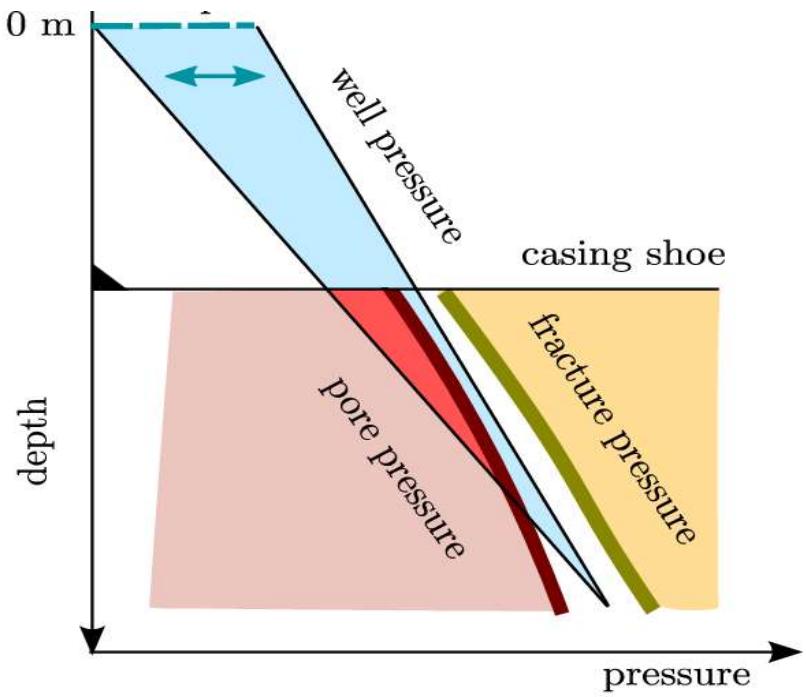


Figure 3. Depth-Pressure Graph Representing the Profile of Fracture Gradient Discovered Through the Application of Leak Off Test, Along the Interval Drilled in OPU Oilfield (Al Ramadan, 2024).

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4.3. Evaluation of Wellbore Stability Conditions of the OPU Oilfield

Using well log-derived rock mechanical properties and in-situ stress estimation, geomechanical modelling was used to assess wellbore stability in the OPU Oilfield in the Niger Delta. Elastic parameters like Young's modulus and Poisson's ratio were computed using density and sonic logs, and overburden and pore pressure data were used to estimate vertical and horizontal stresses. The collapse and fracture limits surrounding the wellbore were determined using the Mohr–Coulomb failure criterion. To determine safe mud weight ranges, Beheshtian et al. (2022) opined that stability envelopes and stress-depth graphs would be created. Zones vulnerable to borehole failure or instability were evaluated using tables summarising computed rock strength parameters, as presented in Table 1.

Table 1. Evaluated Rock Geomechanical parameters in OPU Oilfield (Beheshtian et al., 2022)

Depth (m)	Young’s Modulus (GPa)	Poisson’s Ratio	UCS (MPa)
2000	18	0.28	32
2500	21	0.30	36
3000	24	0.31	40

5. Results and Discussion

5.1. The Formation of Pore Pressure in the OPU Oilfield

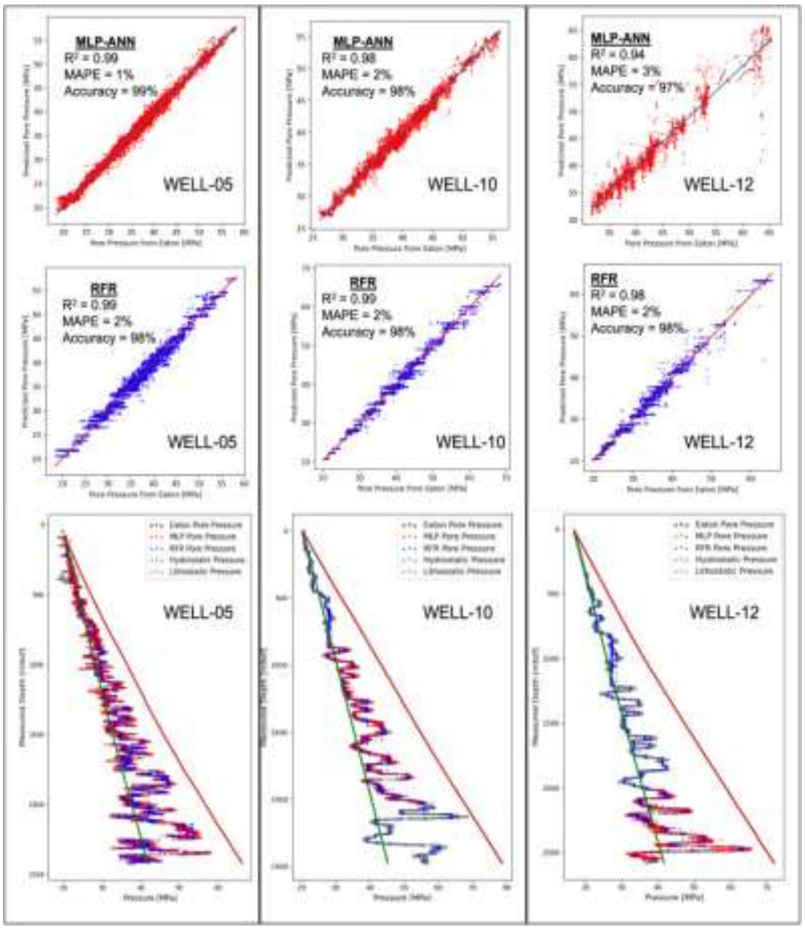

Figure 4. Estimation of Pore Pressure in OPU Oilfield Showing the Predicted Pore Pressure and the Measured (Result) Pore Pressure in Wells 5, 10, and 12, Showing 98% Accurate for Each Well.

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In the OPU Oilfield in the Niger Delta, the pore pressure estimation from well log analysis showed a progressive rise in pressure with depth, with notable deviations from the normal compaction trend at deeper shale intervals, as presented in Figure 4. Abnormal pore pressure zones were found between roughly 2500 and 3200 meters below the surface using Eaton's pore pressure prediction model, as shown in Figure 5. Moderately overpressured formations were indicated by the predicted pore pressure gradients, which ranged from 0.45 to 0.72 psi/ft. Strong agreement with regional pressure trends documented for the Niger Delta basin was confirmed by the produced pore pressure–depth graphs and log overlays. These findings relate to the findings of Alabere and Akangbe (2021), who emphasised how crucial precise pore pressure prediction is for safe mud weight design and drilling operations.

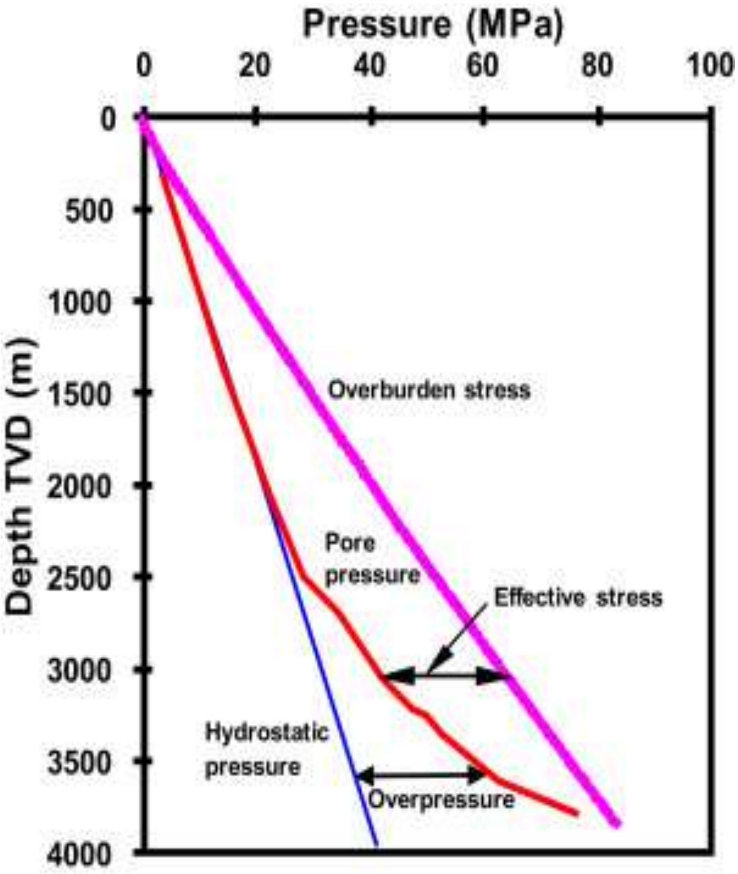

Figure 5. Eaton's Pore Pressure Prediction Model Showing Abnormal Pore Pressure Zones of OPU Oilfield, Showing an Increase in Pressure as the Depth Increases.

5.2. The Fracture Gradient of the Formations within the OPU Oilfield

The fracture gradient gradually rises with depth, according to an analysis of Leak-Off Test (LOT) data from wells in the OPU Oilfield in the Niger Delta. The computed fracture gradient, which shows rising formation strength and overburden stress at deeper intervals, ranged from 0.80 to 0.95 psi/ft, as presented in Table II. The integrity of the casing shoe formations is confirmed by pressure-depth plots, which demonstrate that fracture initiation happened right after the leak-off pressure threshold, as presented in Figure 6. When compared with the study of Mbamalu and Nwosi (2024), for anticipated pore pressure values, the results show a comparatively small drilling window, which is common for many Niger Delta reservoirs. These results highlight how crucial precise fracture gradient estimation is to avoiding lost circulation and guaranteeing safe drilling operations.

Table 2. Leak-Off Test Showing the Increase in Fracture Gradient Based on Depth Increase during Drilling at OPU Oilfield

Casing Shoe Depth (m)	Leak-Off Pressure (psi)	Fracture Gradient (psi/ft)
1500	2200	0.80
2100	3100	0.88
2700	4000	0.95

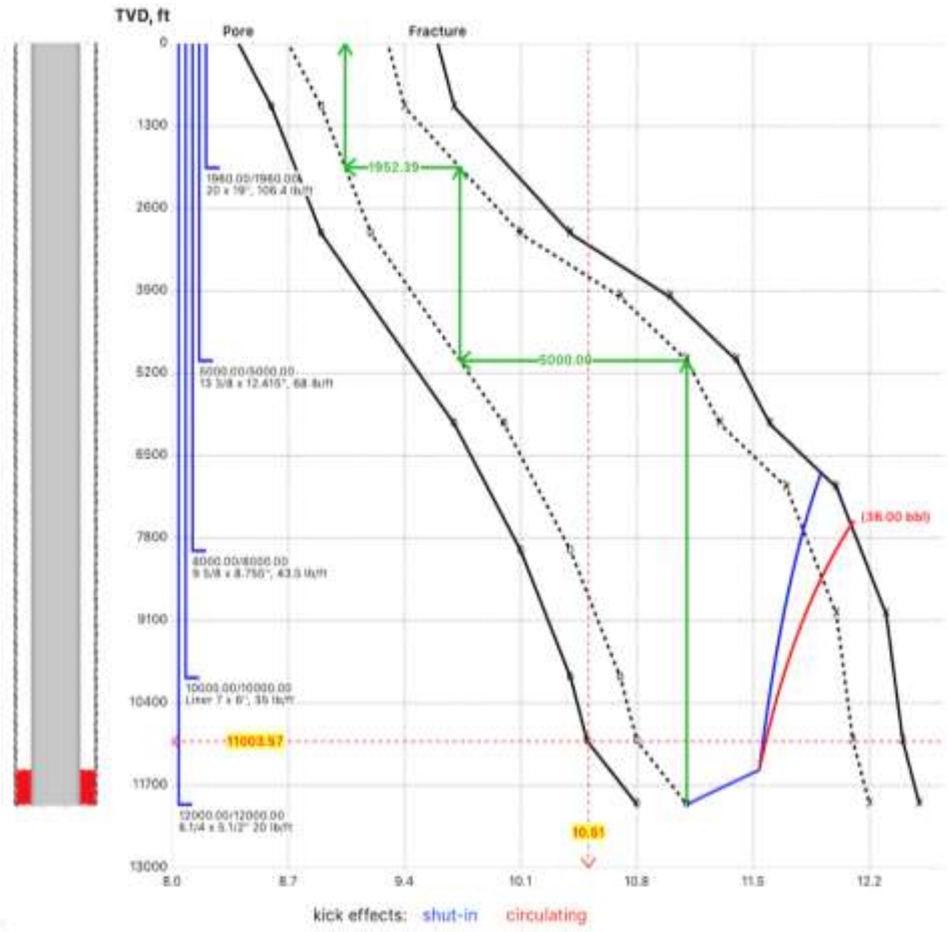

Figure 6. Case Setting Graph Showing the Integrity of the Casing Shoe Formations, Which Indicate the Fracture Gradient Post Leak-Off Pressure Threshold (Mbamalu and Nwosi, 2024).

5.3. The Wellbore Stability Conditions of the OPU Oilfield Formations

The Niger Delta's OPU Oilfield formations' geomechanical analysis showed that wellbore stability conditions varied with depth. Zones vulnerable to collapse and breakout (presented in Figure 7) were identified by the Mohr–Coulomb criterion using elastic properties obtained from sonic and density logs in conjunction with in-situ stress estimates. The estimated safe mud weight window was narrower in overpressured shale intervals, ranging from 12.0 to 14.5 ppg. The majority of formations can be drilled safely if mud weight is kept within these bounds, avoiding both collapse and fracturing, according to stress-depth plots and stability envelopes. These findings are consistent with the study of Adiele et al. (2025), highlighting the need for integrated geomechanical evaluation for optimal drilling design.

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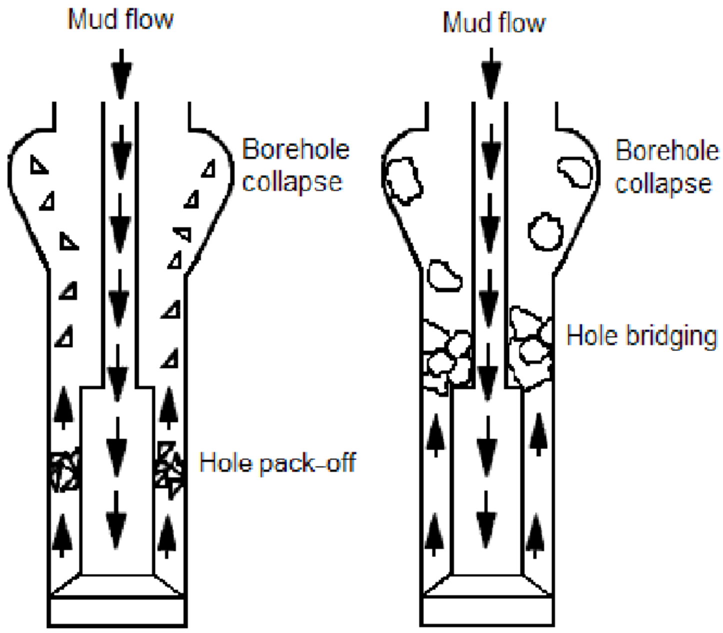

Figure 7. Diagrammatic Representation of Zones Vulnerable to Collapse and Breakout in OPU Oilfield during Drilling in Wells 5, 10 and 12, the Wells Presented in Figure 4 (Adiele et al., 2025).

6. Conclusion and Future Recommendation

The OPU Oilfield's pore pressure and fracture gradient analysis effectively creates a predictive geomechanical model that is essential for reducing drilling risks. This study offers a framework to stop wellbore collapse and lost circulation by precisely identifying overpressure zones and defining the safe mud weight window. Reduced non-productive time and lower operating costs are directly correlated with the ensuing optimised well designs. Through the execution of wellbore integrity from spud to total depth, this analysis improves drilling efficiency and safety. The results help make well-informed decisions about mud programming and casing seat selection, which greatly enhances the strategic development and economic sustainability of hydrocarbon resources in the intricate geological context of the Niger Delta.

The following recommendations are hereby made for future research:

1) There should be an increase in the accuracy of fracture gradient and dynamic pore pressure predictions during operations, through the combination of machine learning models with real-time drilling data.

2) For a better description of subsurface heterogeneity and stress regimes, there should be an application of high-resolution 3D geomechanical models that incorporate seismic inversion.

3) To lower prediction model uncertainty, data collection through more well logs and pressure readings should be increased.

4) There should be an examination of how tectonic pressures and anisotropic rock characteristics affect wellbore stability in intricate Niger Delta formations.

5) To maximise mud weight windows and reduce drilling risks, cutting-edge drilling technology like controlled pressure drilling (MPD) should be applied.

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Declarations

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Competing Interests Statement

The authors have not declared any conflict of interest.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis and manuscript writing equally.

Informed Consent

Not applicable for this study.

Availability of data and material

Supplementary information is available from the authors upon request.

Institutional Review Board Statement

Not applicable for this study.

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